I. INTRODUCTION

Chatham Massachusetts, at the eastern end of Cape Cod, is surrounded by water on three sides, with Nantucket Sound to the south, the Atlantic Ocean and Chatham Harbor to the east, and Pleasant Bay to the north (Figure I-1). Much of the shoreline, especially to the north and south, consists of a number of small embayments of varying size and complexity. These embayments constitute important components of the Town's natural and cultural resources. The nature of enclosed embayments in populous regions brings two opposing elements to bear: as protected marine shoreline they are popular regions for boating, recreation, and land development; as enclosed bodies of water, they may not be readily flushed of the pollutants that they receive due to the proximity and density of development near and along their shores. In particular, the embayments along Chatham's shore are at risk of eutrophication from high nitrogen loads in the groundwater and runoff from their watersheds.

As existing and potentially increasing levels of nutrients impact Chatham's coastal embayments, water quality degradation will continue to harm invaluable environmental resources. As described in the Town's Wastewater Management Planning Study (CWMP), the primary nitrogen source to Chatham's coastal embayments is on-site septic systems via groundwater flow. Although the CWMP provided a cursory analysis of acceptable nitrogen loading to the local estuarine systems based on the methodology developed by the Buzzards Bay Project (USEPA and Massachusetts EOEA, 1991), ecological indictors contradicted many of the results of this analysis.

Since site-specific data have been lacking on existing water quality in the embayments and its relationship to calculated nitrogen loads from their watersheds, the Town implemented a multi-disciplinary approach to resolving estuarine water quality issues. First, the Town's water Quality Laboratory in conjunction with the Chatham Water Watchers (a citizen volunteer organization) implemented a monitoring program of water column nitrogen in 1999. This four-year evaluation has provided the baseline information required for determining the link between upland loading, tidal flushing, and estuarine water quality. Subsequent to the development of a multi-year data set establishing background water quality monitoring for each of the Chatham Embayment systems, and building on previous hydrodynamic and water quality analyses, additional high order biogeochemical analyses and water quality modeling was necessary to develop critical nitrogen targets for each embayment system. These critical nitrogen targets and the link to specific ecological criteria form the basis for the nitrogen threshold limits necessary to complete wastewater master planning and nitrogen management alternatives development in the Town of Chatham. The completion of this complex multi-step process of rigorous scientific investigation supporting watershed based nitrogen management has taken place under the programmatic umbrella of the Massachusetts Estuaries Project. The modeling tools developed as part of this program provide the quantitative information necessary for the CWMP Team to predict the impacts on water quality from a variety of proposed management scenarios.

I.1 THE MASSACHUSETTS ESTUARIES PROJECT APPROACH

Coastal embayments throughout the Commonwealth of Massachusetts (and along the U.S. eastern seaboard) are becoming nutrient enriched. The nutrients are primarily related to

Figure I-1. Study region for the tidal flushing study including the estuarine systems in the Stage Harbor System (outlined in red), the South Coast Embayments (outlined in yellow), and the Pleasant Bay Region (outlined in blue).

changes in watershed land-use associated with increasing population within the coastal zone over the past half century. Many of Massachusetts' embayments have nutrient levels that are approaching or are currently over this assimilative capacity, which begins to cause declines in their ecological health. The result is the loss of fisheries habitat, eelgrass beds, and a general disruption of benthic communities. At its higher levels, enhanced loading from surrounding watersheds causes aesthetic degradation and inhibits even recreational uses of coastal waters. In addition to nutrient related ecological declines, an increasing number of embayments are being closed to swimming, shellfishing and other activities as a result of

bacterial contamination. While bacterial contamination does not generally degrade the habitat, it restricts human uses. However like nutrients, bacterial contamination is related to changes in land-use as watershed become more developed. The regional effects of both nutrient loading and bacterial contamination span the spectrum from environmental to socio-economic impacts and have direct consequences to the culture, economy, and tax base of Massachusetts's coastal communities.

The primary nutrient causing the increasing impairment of the Commonwealth's coastal embayments is nitrogen and the primary sources of this nitrogen are wastewater disposal, fertilizers, and changes in the freshwater hydrology associated with development. At present there is a critical need for state-of-the-art approaches for evaluating and restoring nitrogen sensitive and impaired embayments. Within Southeastern Massachusetts alone, almost all of the municipalities (as is the case with the Town of Chatham) are grappling with Comprehensive Wastewater Planning and/or environmental management issues related to the declining health of their estuaries.

Municipalities are seeking guidance on the assessment of nitrogen sensitive embayments, as well as available options for meeting nitrogen goals and approaches for restoring impaired systems. Many of the communities have encountered problems with "first generation" watershed based approaches, which do not incorporate estuarine processes. The appropriate method must be quantitative and directly link watershed and embayment nitrogen conditions. This "Linked" Modeling approach must also be readily calibrated, validated, and implemented to support planning. Although it may be technically complex to implement, results must be understandable to the regulatory community, town officials, and the general public.

The Massachusetts Estuaries Project represents the next generation of watershed based nitrogen management approaches. The Massachusetts Department of Environmental Protection (MA DEP), the University of Massachusetts – Dartmouth School of Marine Science and Technology (SMAST), and others including the Cape Cod Commission (CCC) have undertaken the task of providing a quantitative tool for watershed-embayment management for communities throughout Southeastern Massachusetts.

The Massachusetts Estuary Project is founded upon science-based management. The Project will use a consistent, state-of-the-art approach throughout the region's coastal waters and provide technical expertise and guidance to the municipalities and regulatory agencies tasked with their management, protection, and restoration. The overall goal of the Massachusetts Estuaries Project is to provide the DEP with technical guidance to support policies on nitrogen loading to embayments. In addition, the technical reports prepared for each embayment system will serve as the basis for the development of Total Maximum Daily Loads (TMDLs). Development of TMDLs is required pursuant to Section 303(d) of the Federal Clean Water Act. TMDLs must identify sources of the pollutant of concern (in this case nitrogen) from both point and non-point sources, the allowable load to meet the state water quality standards and then allocate that load to all sources taking into consideration a margin of safety, seasonal variations, and several other factors. In addition, each TMDL must contain an implementation plan. That plan must identify, among other things, the required activities to achieve the allowable load to meet the allowable loading target, the time line for those activities to take place, and reasonable assurances that the actions will be taken.

In appropriate estuaries, TMDL's for bacterial contamination will also be conducted in concert with the nutrient effort (particularly if there is a 303d listing). However, the goal of the bacterial program is to provide information to guide targeted sampling for specific source

identification and remediation. As part of the overall effort, the evaluation and modeling approach will be used to assess available options for meeting selected nitrogen goals, protective of embayment health.

The major Project goals are to:

- develop a coastal TMDL working group for coordination and rapid transfer of results,
- determine the nutrient sensitivity of each of the 89 embayments in Southeastern MA
- provide necessary data collection and analysis required for quantitative modeling,
- conduct quantitative TMDL analysis, outreach, and planning,
- keep each embayment's model "alive" to address future regulatory needs.

The core of the Massachusetts Estuaries Project analytical method is the Linked Watershed-Embayment Management Modeling Approach. This approach represents the "next generation" of nitrogen management strategies. It fully links watershed inputs with embayment circulation and nitrogen characteristics. The Linked Model builds on well accepted basic watershed nitrogen loading approaches such as those used in the Buzzards Bay Project, the CCC models, and other relevant models. However, the Linked Model differs from other nitrogen management models in that it:

- requires site specific measurements within each watershed and embayment;
- uses realistic "best-estimates" of nitrogen loads from each land-use (as opposed to loads with built-in "safety factors" like Title 5 design loads);
- spatially distributes the watershed nitrogen loading to the embayment;
- accounts for nitrogen attenuation during transport to the embayment;
- includes a 2D or 3D embayment circulation model depending on embayment structure;
- accounts for basin structure, tidal variations, and dispersion within the embayment;
- includes nitrogen regenerated within the embayment;
- is validated by both independent hydrodynamic, nitrogen concentration, and ecological data;
- is calibrated and validated with field data prior to generation of "what if" scenarios.

The Linked Model has been applied for watershed nitrogen management in ca. 15 embayments throughout Southeastern Massachusetts. In these applications it has become clear that the Linked Model Approach's greatest assets are its ability to be clearly calibrated and validated, and its utility as a management tool for testing "what if" scenarios for evaluating watershed nitrogen management options.

The Linked Watershed-Embayment Model when properly parameterized, calibrated and validated for a given embayment becomes a nitrogen management planning tool which fully supports TMDL analysis. The Model suggests "solutions" for the protection or restoration of nutrient related water quality and allows testing of "what if" management scenarios to support evaluation of resulting water quality impact versus cost (i.e., "biggest ecological bang for the buck"). In addition, once a model is fully functional it can be "kept alive" and corrected for continuing changes in land-use or embayment characteristics (at minimal cost). In addition, since the Model uses a holistic approach (the entire watershed, embayment and tidal source waters), it can be used to evaluate all projects as they relate directly or indirectly to water quality conditions within its geographic boundaries.

Linked Watershed-Embayment Model Overview: The Model provides a quantitative approach for determining an embayment's: (1) nitrogen sensitivity, (2) nitrogen threshold

loading levels (TMDL) and (3) response to changes in loading rate. The approach is fully field validated and unlike many approaches, accounts for nutrient sources, attenuation, and recycling and variations in tidal hydrodynamics (Figure I-2). This methodology integrates a variety of field data and models, specifically:

- Monitoring - multi-year embayment nutrient sampling
- Hydrodynamics -
  - embayment bathymetry
  - site specific tidal record
  - current records (in complex systems only)
  - hydrodynamic model
- Watershed Nitrogen Loading
  - watershed delineation
  - stream flow (Q) and nitrogen load
  - land-use analysis (GIS)
  - watershed N model
- Embayment TMDL - Synthesis
  - linked Watershed-Embayment N Model
  - salinity surveys (for linked model validation)
  - rate of N recycling within embayment
  - D.O record
  - Macrophyte survey
  - Infaunal survey (in complex systems)

I.2 SITE DESCRIPTION

The coast of Chatham is bordered to the south by Nantucket Sound, the east by the Atlantic Ocean, and the north by Pleasant Bay. For this study, Chatham's estuarine systems have been separated into three general groups: the 1) Stage Harbor System, 2) the South Coast Embayments and the 3) Pleasant Bay Region Embayments (see Figure I-1).

Although the three estuarine systems along the south shore (Stage Harbor, Sulphur Springs, and Taylors Pond) exhibit different hydrologic characteristics, ranging from expansive salt marshes to flooded kettle ponds, the tidal forcing for these systems is generated from Nantucket Sound. In contrast, water propagating through the Chatham Harbor/Pleasant Bay system is derived from the Atlantic Ocean.

The south shore of Chatham exhibits a moderate tide range, with a mean range of about 4.5 ft. Since the water elevation difference between Nantucket Sound and each of the estuarine systems is the primary driving force for tidal exchange, the local tide range naturally limits the volume of water flushed during a tidal cycle. Tidal damping (reduction in tidal amplitude) through the Stage Harbor system is negligible indicating "well-flushed" systems. In contrast, the tidal attenuation caused by the restrictive channels and marsh plains within the South Coast Embayments of Mill Creek/Taylors Pond is indicative of a "restrictive" system, where tidal flow and the associated flushing are inhibited. Based on the tidal characteristics alone, this might indicate that the Stage Harbor embayments (e.g. Little Mill Pond) are "healthy" relative to the embayments further the west; however, land development in the southeastern portion of Chatham likely provides a substantially higher nutrient load to the Stage Harbor embayments. Consequently, estuarine water quality may be more dependent on nutrient loading than tidal characteristics for these systems.

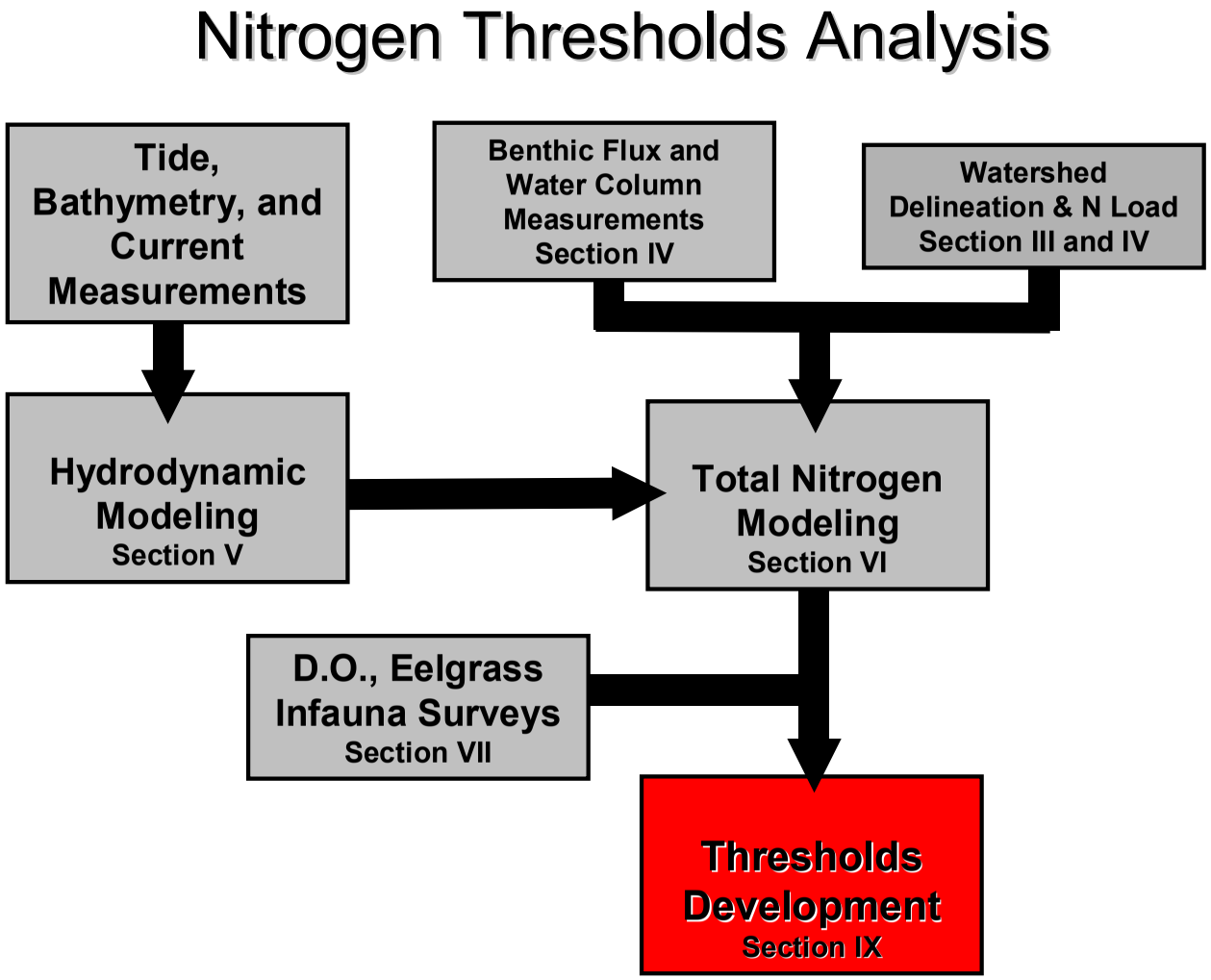

Figure I-2. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach

The Stage Harbor System consists of six (6) embayments: Stage Harbor, Oyster Pond River, Oyster Pond, Mitchell River, Mill Pond, and Little Mill Pond. The watershed for this estuarine system contains approximately 1,700 acres dominated by single family residences. As stated above, land development in the southeastern portion of Chatham creates a large nutrient load to the Stage Harbor System. Based on watersheds developed by the Cape Cod Commission (Stearns & Wheler, 1999), the nitrogen loading from the more heavily populated areas of the village and the area to the west is focused on the northern reaches of the estuarine system. For example, approximately 80% of the nitrogen load from single-family dwellings enter the Stage Harbor System along the shorelines of Oyster Pond, the northern portion of Oyster Pond River, Little Mill Pond, and Mill Pond.

The South Coast Embayments exhibit similar nitrogen loading characteristics, where much of the nutrient loading enters the system along the northern limits. Due to the relatively narrow channels that connect the upper portions of these embayments to Nantucket Sound, flushing characteristics are relatively poor. However, the large expanses of salt marsh in Mill Creek and the Cockle Cove Creek/Sulphur Springs systems allow these water bodies to be more tolerant of high nitrogen loads.

Within Pleasant Bay, the tide propagating through New Inlet and Chatham Harbor is significantly attenuated by the series of flood tidal shoals within the inlet throat. The mean tide range drops from just under 8 feet in the Atlantic Ocean to around 5 feet at the Chatham Fish Pier. Only minor attenuation occurs between the Fish Pier and Pleasant Bay; however, smaller sub-embayments separated from the main system by culverts exhibit significant additional tidal attenuation. Both Muddy Creek and Frost Fish Creek have mean tide ranges of less than 1 ft. For the Bassing Harbor system, nitrogen loading is primarily focused in the Frost Fish Creek and Ryder Cove watersheds.

In addition to tidal forcing characteristics, the regional geomorphology influences flushing characteristics and the associated water quality within embayments along the south shore, as well as for the Pleasant Bay system. Shoaling along the south shore of Chatham has caused the opening and closing of several inlets to the Sulphur Springs/Bucks Creek/Cockle Cove Creek system during the past 50 years. In addition, stability issues concerning the Stage Harbor navigation channel required repositioning of the inlet in 1965 as a result of regional shoaling. The most dramatic recent change in local geomorphology occurred in early 1987, when New Inlet formed east of the Chatham Lighthouse. From a tidal flushing and water quality perspective, the resulting increase in tide range within Pleasant Bay of approximately 1 ft caused a substantial improvement of regional tidal exchange.

I.3 NITROGEN LOADING

Surface and groundwater flows are pathways for the transfer of land-sourced nutrients to coastal waters. Fluxes of primary ecosystem structuring nutrients, nitrogen and phosphorus, differ significantly as a result of their hydrologic transport pathway (i.e. streams versus groundwater). In sandy glacial outwash aquifers, such as in the Chatham area, phosphorus is highly retained during groundwater transport as a result of sorption to aquifer mineral (Weiskel and Howes 1992). Since even Cape Cod “rivers” are primarily groundwater fed, watersheds tend to release little phosphorus to coastal waters. In contrast, nitrogen, primarily as plant available nitrate, is readily transported through oxygenated groundwater systems on Cape Cod (DeSimone and Howes 1998, Weiskel and Howes 1992, Smith *et al.* 1991). The result is that terrestrial inputs to coastal waters tend to be higher in plant available nitrogen than phosphorus (relative to plant growth requirements). However, coastal estuaries tend to have algal growth

limited by nitrogen availability, due to their flooding with low nitrogen coastal waters (Ryther and Dunstan 1971). Tidal embayments in Chatham follow this general pattern, where the primary nutrient of eutrophication in these systems is nitrogen.

Nutrient related water quality decline represents one of the most serious threats to the ecological health of the nearshore coastal waters. Coastal embayments, because of their shallow nature and large shoreline area, are generally the first indicators of nutrient pollution from terrestrial sources. By nature, these systems are highly productive environments, but nutrient over-enrichment of these systems world-wide is resulting in the loss of their aesthetic, economic and commercially valuable attributes.

Each embayment system maintains a capacity to assimilate watershed nitrogen inputs without degradation. However, as loading increases a point is reached at which the capacity (termed assimilative capacity) is exceeded and nutrient related water quality degradation occurs. As nearshore coastal salt ponds and embayments are the primary recipients of nutrients carried via surface and groundwater transport from terrestrial sources, it is clear that activities within the watershed, often miles from the water body itself, can have chronic and long lasting impacts on these fragile coastal environments.

Protection and restoration of coastal embayments from nitrogen overloading has resulted in a focus on determining the assimilative capacity of these aquatic systems for nitrogen. While this effort is ongoing (e.g. USEPA TMDL studies), southeastern Massachusetts has been the site of intensive efforts in this area (Eichner et al., 1998, Costa et al., 1992 and in press, Ramsey et al., 1995, Howes and Taylor, 1990, and the Falmouth Coastal Overlay Bylaw). While each approach may be different, they all focus on changes in nitrogen loading from watershed to embayment, and aim at projecting the level of increase in nitrogen concentration within the receiving waters. Each approach depends upon estimates of circulation within the embayment; however, few directly link the watershed and hydrodynamic models, and virtually none include internal recycling of nitrogen (as was done in the present effort). However, determination of the “allowable N concentration increase” or “threshold nitrogen concentration” used in previous studies had a significant uncertainty due to the need for both linked watershed-embayment modeling and site specific data. In the present effort we have integrated site-specific data on nitrogen levels and the gradient in N concentration and ecological health within the embayments monitored by Chatham citizens and site-specific habitat quality data (D.O., eelgrass, phytoplankton blooms, benthic animals) to “tune” general thresholds used by the Cape Cod Commission, Buzzards Bay Project, and Massachusetts State Regulatory Agencies.

Unfortunately, almost all of Chatham’s estuarine systems are near or beyond their ability to assimilate additional nutrients without impacting their ecological health. The effect is that nitrogen management of these systems is aimed at restoration, not protection or maintenance of existing conditions. In general, nutrient over-fertilization is termed “eutrophication” and when the nutrient loading is primarily from human activities, “cultural eutrophication”. Although the influence of man-induced changes has increased nitrogen loading to the systems and contributed to the degradation in ecological health, eutrophication of several Chatham embayments would occur without man’s influence. As part of future restoration efforts, it is important to understand that it may not be possible to turn each embayment into a “pristine” system.

I.4 WATER QUALITY MODELING

Evaluation of upland nitrogen loading (Stearns & Wheler, 1999 and more recent updates to watershed boundaries by USGS and nitrogen loading by the CCC) provides important "boundary conditions" for water quality analyses of Chatham's coastal embayments; however, a thorough understanding of estuarine circulation is required to accurately determine nitrogen concentrations within each system. Therefore, water quality modeling of tidally influenced estuaries must include a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Numerical models provide a cost-effective method for evaluating tidal hydrodynamics since they require limited data collection and may be utilized to numerically assess a range of management alternatives. Once the hydrodynamics of an estuary system are understood, computations regarding the related coastal processes become relatively straightforward extensions to the hydrodynamic modeling. The spread of pollutants may be analyzed from tidal current information developed by the numerical models.

The water quality evaluation examined the potential impacts of nitrogen loading into the Stage Harbor System, the South Coast Embayments, and the Pleasant Bay Region. A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for each of the systems. Once the hydrodynamic properties of each estuarine system were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates.

Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic models were then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis. Almost all nitrogen entering Chatham's coastal embayments is transported by freshwater, predominantly groundwater. Concentrations in Nantucket Sound and Pleasant Bay source waters were taken from Chatham Water Watchers and Pleasant Bay Alliance data. Measurements of current nitrogen distributions throughout estuarine waters were used to calibrate the water quality model (under existing loading conditions).

I.5 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project linked watershed-embayment approach to the Town of Chatham coastal embayment systems. A review of existing water quality studies is provided (Section II). The development of the watershed delineations and associated detailed land use analysis for watershed based nitrogen loading to the coastal system is described in Sections III and IV. In addition, nitrogen input parameters to the water quality model are described. Since benthic flux of nitrogen from bottom sediments is a critical (but often overlooked) component of nitrogen loading to shallow estuarine systems, determination of the site-specific magnitude of this component also was performed (Section IV). Nitrogen loads from the watersheds surrounding each estuary were derived from Cape Cod Commission data and offshore water column nitrogen values were derived from an analysis of monitoring stations in Chatham Harbor and Nantucket Sound (Section IV). Intrinsic to the calibration and validation of the linked-watershed embayment modeling approach is the collection of background water quality monitoring data (conducted by municipalities) as discussed in Section IV. Results of hydrodynamic modeling of embayment circulation are discussed in Section V and nitrogen (water quality) modeling, as well as an analysis of how the measured nitrogen levels correlate to observed estuarine water

quality are described in Section VI. In addition, an ecological assessment of all coastal embayments was performed that included a review of existing water quality information and the results of a benthic analysis (Section VII). This assessment can be used by the Town to develop a baseline for future management and estuary restoration efforts.

Analyses of Chatham's coastal embayments were performed to assist the Town with future management decisions, beginning with those embayments where flushing improvements were considered (e.g. Muddy Creek). The results of the nitrogen modeling for each scenario have been presented (Section IX).